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ABSTRACT

The natural river processes along a 30 m high riverbank of one of the largest tributaries to Lake Superior cause periodic landslides. After arresting toe erosion, local authorities needed to protect the infrastructure at the crest from further damage as the slope continued to flatten towards its long-term angle of repose. A long-term hazard management strategy was applied using the cautionary zone approach (CZA). Design criteria included a target safety factor, no construction impacts, no maintenance and a 75-year design life. The solution drew from 3 technologies: soil nails, laterally loaded piles and biotechnical stabilization. Steel nails, 35 mm diameter, were designed in bending perpendicular to slip surfaces and installed on a 1 to 1.5 m grid. Lightweight equipment working on the slope installed the 4 to 12 m long nails very rapidly without drilling or grouting. For shallow flow slides around a rigid nail, plate heads were added. A facing of roots controlled soil movements between nails and provided a natural look with the system completely out of sight. Three years of performance monitoring data are presented, and confirm a successful case history. This paper describes an innovative approach used to stabilize a landslide prone area in an urban environment.

INTRODUCTION

Several solutions are available for unstable over-steepened slopes. These include flattening, drainage, soil improvement, mechanical reinforcement or retaining systems. A recent innovative development is a hybrid of these, integrating reinforcement as well as retaining concepts. The system, using small laterally loaded steel nails with plate heads and a vegetation root facing, was used in 2004 to successfully stabilize a 30 m high slope in Canada. This system eliminated the need for traditional drilling, grouting and shotcrete, providing a low cost solution with a completely natural look.

The case study of this slope involves the riverbanks along the Kaministiquia River, one of the largest tributaries to Lake Superior. The river meanders through a deeply incised floodplain of the Kaministiquia delta, with 30 m high valley sides (Figure 1). The river travels through an urban area of Thunder Bay, the 10th largest city in Ontario, on the shore of Lake Superior. Over recent decades the outside of a meander has encroached on a developed area in one area of the city, creating a hazard for a street, watermain and many houses. The active erosion has created riverbank slopes from 27° in the gullies to 45° at the promontories (Figure 2).

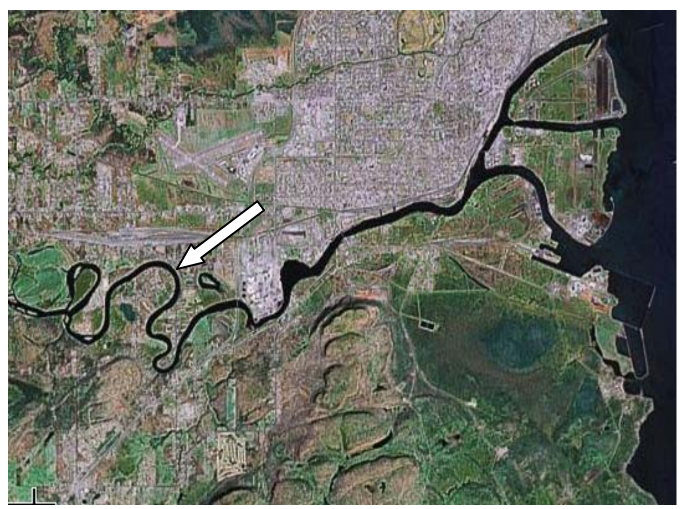

Fig. 1. Site location in Thunder Bay

In the 1970's technical studies concluded that the erosion was a natural phenomenon unrelated to development, that its average regression rate in a riverbank consisting of sands, silts and clays was 0.5 m per year, and that a long history of observations indicated that regression occurred with slides that were always shallow (Fabius & Suke, 1990). In the early 1980's, the street (the only link to a residential

Fig. 2. Active erosion on the Kaministiquia River

neighbourhood) and several houses near the crest of the riverbank were in imminent danger. In response, the local authority (the Lakehead Region Conservation Authority or LRCA) purchased and demolished several homes, and contracted out the riprap toe protection of more than a kilometre of riverbank to arrest the toe erosion (Figure 3). Furthermore, 350 m of slope that had encroached within a few metres of the street was stabilized with a retaining structure at the crest. The design consisted of 12 m long soldier piles with 6m of concrete lagging and tied back under the street to bored pile deadmen. The slope below was left to gradually reach its own equilibrium without regrading or revegetation.

The landslide hazards along the remainder of the riverbank (now with riprap toe protection) were managed using the cautionary zone approach (CZA). With this method, described in detail by Fabius et al. 2004, a cautionary zone is established adjacent each facility to be protected, and no action needs to be taken until the crest of the slope encroaches on the cautionary zone. In this case, based on observations that slides were always shallow, the cautionary zone was set at 20 feet wide for the street and 33 feet for houses. A theoretical basis for the CZA has since been developed for this method using unsaturated soil mechanics and it was successful in delaying the need by the LRCA to fund stabilizing measures over the next 20 years as the slope crest regressed.

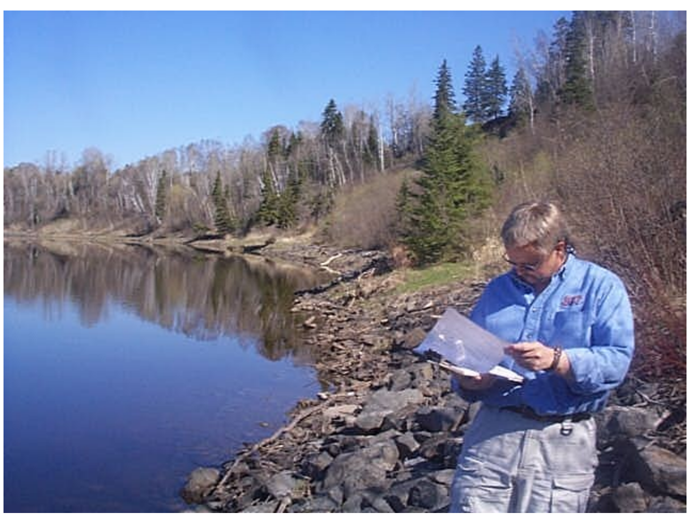

Fig. 3. With the toe erosion arrested, the slope crest continues to regress to its angle of repose.

By 2004 the slope had encroached within the street's cautionary zone at 5 locations, and the LRCA tendered out a design-build contract for the 5 sites with a specified safety factor of 1.3 and a 75 year design life. The successful bid, the lowest cost by far, was a system of 35 mm diameter steel soil nails up to 12 m long, installed perpendicular to the slope on a 1 to 1.5 m grid (Figure 4). Special heads and a biotechnical facing over the slope were key elements of the system. Installation was with lightweight equipment working on the slope and installed the nails without drilling or grouting, and without affecting use of the street at the crest. The system has been used in Canada since the 1990's.

This paper describes the design and installation of this innovative soil nail and root technology (SNART). The design is discussed in terms of soil properties including effects of over-consolidation ratio and soil suction, nail resistance as it varies with depth, failure modes, corrosion protection, root design and nail head design. The construction is described and the results of post construction monitoring presented.

TECHNOLOGY DEVELOPMENT

The development of the system as it stands today was not a sudden 'breakthrough' idea. Instead it was an incremental response to highly motivated customers aggressively pushing engineers and constructors to provide a more cost effective solution to slope problems that have numerous constraints.. For example, there was a common requirement that the system could be installed quickly with minimal disruption to local services, the environment and neighbouring land owners. Furthermore, there was a significant advantage to a system that could be installed with lightweight equipment working on the slope and when complete would look natural.

The key to the solution was found to be soil nails. However, the traditional shotcrete facing was determined unacceptable: too costly and susceptible to frost action. Roots proved to be a better facing solution, similar to nail reinforcement but shorter, at a much closer spacing, and very effective for arresting slips between nails. Simple direct shear test methods were developed to quantify root strength.

The traditional drilling and grouting of nails was also unacceptable, again too costly. Instead, 3 alternate insertion methods were developed depending on soil type and

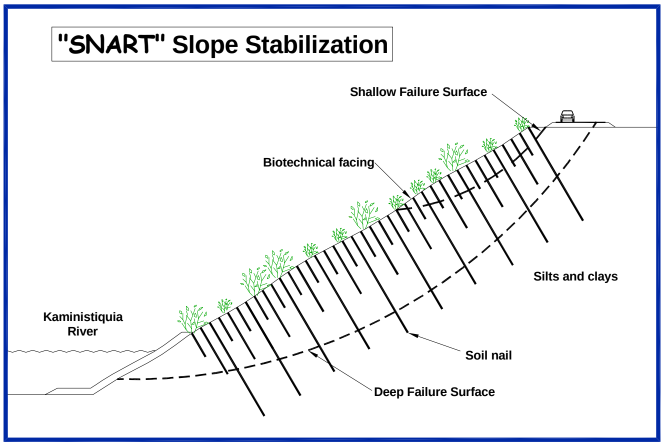

Fig. 4. Soil nail and root technology for riverbank stabilization.

condition: percussion (pile driving analogy), vibration (vibratory hammer analogy) and rotation (helical anchor analogy). The emphasis was on 'green' methods, minimizing disturbance.

In addition, the need for tension capacity in the nails was eliminated by installing the nails perpendicular to the slip failure. This required analytical design techniques similar to laterally loaded piles as well as adding the concept of local shear in bearing, and modeling the soil flowing around a narrow rigid member. It was found that the latter failure mode becomes critical at shallow depths, typically less than 2 m, and that the nails themselves were not wide enough to prevent it. As such various configurations of nail heads were tested in a tilted sand box with full size instrumented nails. This resulted in a plate being added to the top of the nail, oriented transverse to the slope and slightly below ground (Tozer & Fabius, 2000). The solution was found to be very effective for stabilizing over-steepened granular embankment slopes.

Later, when looking for a solution for an unstable side-hill fill, efficient splicing methods were developed for installing these nails up to 20 m deep. In addition, for railway stabilizations, a method was developed for installing nails on slopes up to 45^0 using a small walking excavator, eliminating the need for any track time at all.

Concerns with longevity of the steel are addressed with either coatings (in aggressive soils) or sacrificial allowances (low aggressive soils). While traditional soil nails designed in tension are highly susceptible to significant losses in capacity from stress concentrations caused by even localized corrosion such as pitting, the SNART system nails rely on bending and shear of the steel and do not have this weakness.

With design and installation issues resolved, the SNART system is applied today typically to over-steepened slopes up to 45^0 and where the slip zone, if a failure has occurred, is relatively thin. It is most often used where a no-maintenance solution with a natural look is desired, and also when a surgical application is preferred to a large scale structure.

THE KAMINISTIQUIA RIVER CASE STUDY

At the 5 Kaministiquia River sites, soil conditions comprise an upper 3 m of sand over a deep deposit of non plastic silt, faintly varved, extending to more than 20 m below river level. The silt is compact with some dense zones.

Monitoring found that the main water table has a maximum level at 22 m below the crest at elevation 187.4 m as measured over the course of 1982. A higher level at 189 m was selected for design, based on engineering judgment. A minimum water table at 185 m was selected, 2 m above nearby Lake Superior where the river discharges. Stratigraphy has been discussed in detail by Fabius and Suke, 1990.

For soil nail design on slopes less than 45^0, past experience (e.g. Tozer and Fabius, 2000) has found that the design with respect to lateral nail resistance in bending is very sensitive to the angle of internal friction of the soil. For example, a 2-degree increase in the friction angle can reduce the number of nails by 15 to 20%. Designing the geotechnical investigation to establish accurate (rather than simply conservative) soil strength parameters is therefore quite valuable for SNART solutions.

Boreholes at the top of the Kaministiquia River slope, readily accessible to geotechnical drill rigs, indicated a soil that was lightly over-consolidated. However given that the slope has been created through erosion by the river at the toe, it was expected that the degree of over-consolidation would increase down-slope where it had once supported many feet of overburden. This meant that within the stress range of typical slide surfaces, the angle of internal friction would increase as well. Additional samples were subsequently obtained down the slope and the higher ϕ' confirmed with a few direct shear tests. The soil nevertheless exhibited a ductile failure with little post peak strength reduction.

For the soils located behind the crest normally consolidated strengths were selected with a friction angle ϕ' of 30^o. Over-consolidated soil parameters with ϕ' of 34^o and c' of nil were assigned to the slope in front of the crest (although direct shear testing indicated a wide range of friction angles from 34^o to 46^o). Within 2 m of the slope surface itself, the soil strength was modeled as normally consolidated to account for frost action and desiccation effects.

SNART Design

The design of the soil nail and root technology for the Kaministiquia River slope has been described in detail by Fabius et. al. (2005). For the five areas where the crest had regressed to within 6 m of the edge of the road, the overall slope angle varies from 25 to 30°. The total height of slope is 30 m of which 4.5 m is below river level.

Slope Stability Analyses. Three modes of slope failure were analyzed: wedge, rotational and translational slides. Of these, rotational failures were found to control the soil nail design and spacing for deep-seated failures (typically at depths of 3 to 10 m). The translational slides control the shallow soil nail spacing, the plate head requirements and the facing design. Three-dimensional analyses were applied for small failures between the nails.

Rotational slip surfaces were analyzed using Slope/W (by Geo-Slope International) and the Morgenstern-Price method. To find the reinforcement zone where failure surfaces have a degree of safety less than the target, safety factor zones were mapped. The depth of the zone containing slips with a safety factor of less than 1.3 typically varied from 8 to 11 m deep at the 5 sites.

Nail-Soil Interaction. Given the design concept of orienting the nails perpendicular to the slope, the design against a slope failure through the reinforced zone was based on the bending moment and shear resistance of the steel nails. Analyses found that the design was controlled by the maximum allowable bending moment. Furthermore, it was found that at shallow depths the steel bars by themselves were not wide enough to deal with failures between the reinforcing. In particular, plate heads and light surficial root reinforcing were integral components needed in the design.

Analyses of the nail-soil interaction were carried out using 3 methods: (a) in accordance with traditional bearing capacity theory (local shear by Vesic, 1963), (b) the general approach for laterally loaded soil nails outlined by USDOT (1994) and (c) utilizing a soil structure interaction analyses program for laterally loaded piles and shafts (LPILE).

Static analyses were first carried out to determine nail resistances both above and below a slip plane using the local bearing capacity of the soil along the bar and the moment capacity of the nail. The first case (Figure 5) assumes that the nail is held rigidly below the slip surface and the available nail resistance is limited by the length of nail provided above the slip surface. At ultimate failure, the nails remain embedded within the slope as the soil mass flows around the nail. This failure mode becomes critical for slides at shallow depth (typically less than 2 m). For the nails to provide adequate resistance at these depths, the spacing of the nails would have to be so close that it became uneconomical. Therefore, the nails were designed with special plate heads (Figure 5) oriented transversely to the slope (similar to 'plate piles' described by Short and Collins, 2006).

The second case (Figure 6) assumes that the depth of the slip surface is sufficient to fix the upper portion of the nail within

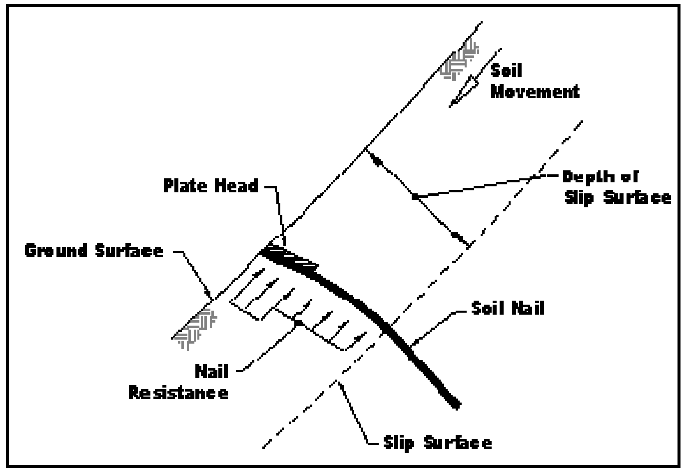

Fig. 5. Shallow flow failure mode with nail and plate head.

the sliding mass. In this case, the length of the nail available to mobilize resistance below the slide is a function of the stiffness of both nail and the soil. The available soil nail resistance is a function of the nail properties, soil properties and confining stress or depth. The nail resistance increases significantly with depth.

For each of the two failure modes the resistance was plotted with depth. The two were combined to provide the minimum resistance at each depth, resulting in the design nail resistance chart used for input into stability analyses of the reinforced slope (Figure 7).

A design criteria of 25 mm was established for surficial deformations, although in actual fact the slope, street and watermain can likely accommodate much more. An assessment of lateral deflections required to mobilize the soil nail resistance was therefore carried out, utilizing LPILE software by Ensoft. For this soil, a thin failure zone was assumed, essentially without a weakened slip zone. The nail resistances determined were close to and slightly higher than

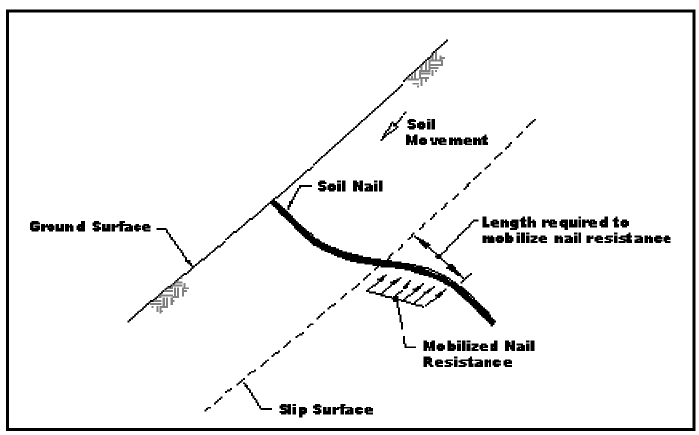

Fig. 6. Deep failure mode with nail.

those calculated with the previously noted bearing capacity

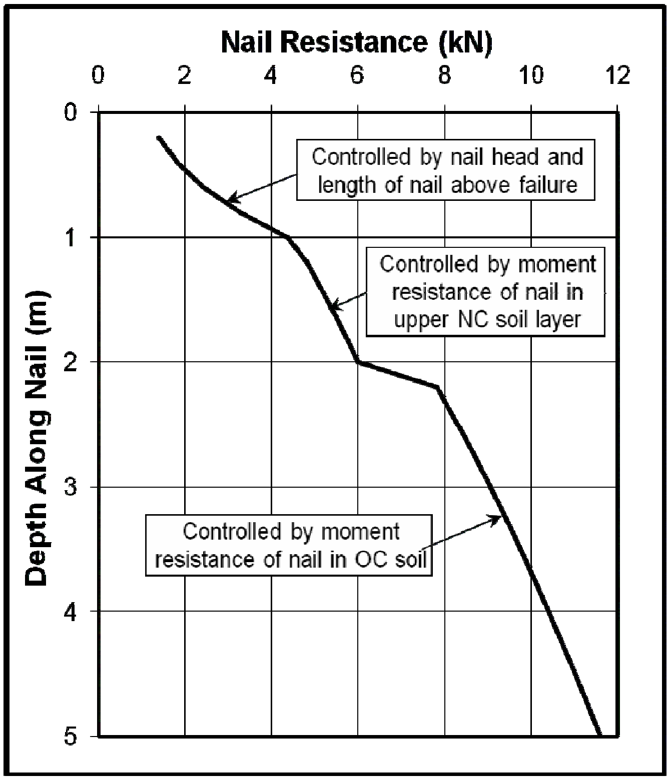

Fig. 7. Typical lateral nail resistance variation with depth

method. Lateral deflections were calculated at 5 to 20 mm within the upper 1 m of the slope surface, 3 to 5 mm within a depth of 1 to 2 m, and less than 3 mm below a depth of 2 m.

The deflection analysis also confirmed that the length of bar required to mobilize the full soil nail resistance varies from 1 m near the slope surface to less than 0.3 m at a depth of 10 m. This value determined the minimum depth below the critical slip plane that the nails needed to penetrate.

As a check against highly stressed localized plastic zones that may develop in the soil outside of a reinforced zone, a simple finite element analyses was carried out. This confirmed that such zones were not a concern. The latter is typically not addressed in conventional soil nail design (e.g. if a large weakened zone were to develop prior to failure, then a soil nail, whether in tension or in bending, may be under-designed if a thin slip surface had been assumed). Nevertheless, it is a particular important issue for a slender member like a soil nail acting in bending which requires sufficient stiffness to reinforce across the weakened zone (see, for example, Cornforth, 2005). With the post peak strength loss less than 5%, analyses ruled out the concern of developing a wide low strength failure zone.

Soil Nail Lengths. The distribution of soil nails with depth was optimized through a comparison of the resistance at various depths required to achieve the desired safety factor, with the nail resistance available as determined through nail-soil interaction analyses. Given that both the safety factor against sliding and the nail resistance increase with depth, the density of nails required decreases with depth. The optimal nail layout on the slope was found to be a diamond pattern, with each horizontal row offset from the adjacent one. Nail spacings varied from 0.9 to 1.5 m, dependant on local slope angles (Figure 8).

Design Life. The nails selected were 35 mm diameter steel concrete reinforcing bar with yield strength of 400 MPa. The

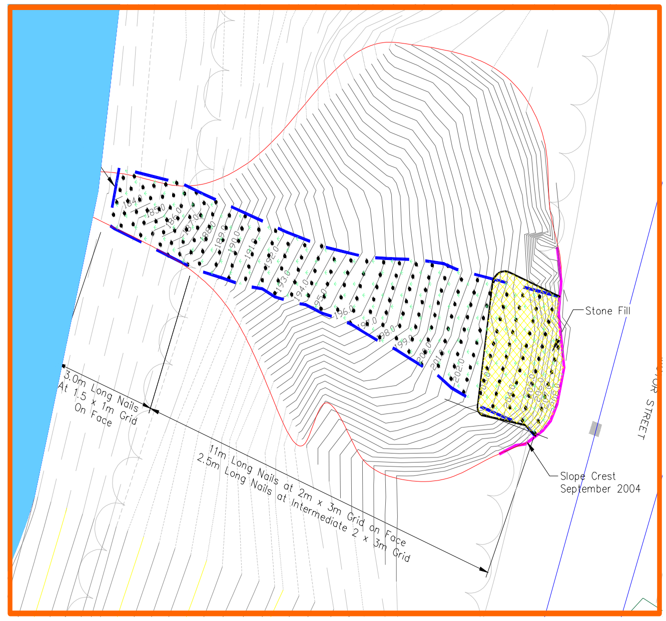

Fig. 8. Nail layout for Site 5..

sacrificial approach to corrosion was applied for long-term performance at this site. The allowance was determined based on actual corrosion of steel plates buried in the ground for many years (Murray, 1982). This approach ranks corrosiveness based on several factors and determined a maximum sacrificial thickness of less than 1.5 mm for the steel surface was required. The suitability of this design is confirmed with typical design allowances for soil reinforcement in tension (e.g. Elias, 1996). Welds were designed for installation stresses without the need for long term performance.

Facing Design. A facing was needed to control shallow soil movements between nails. At times of zero soil suction (i.e. when the soils above the water table saturate during prolonged rainfall) the soils at this site are prone to shallow sloughing at slope angles approaching or exceeding the angle of internal friction of the soil. Under these conditions, soil nails alone are not a cost effective means of improving stability for failures between the nails. The depth and stability for these shallow sloughs are influenced by the nail spacing, plate size at the nail head, saturated soil strength and the slope angle. For this project, the facing required soil strengthening to depths of 0.1 to 0.3 m, depending on slope angle, with a few localized steep areas requiring up to 0.45 m.. This was accomplished with an accomplished with an apparent cohesion provided by roots.

A local grass mix design was assessed. Several direct shear tests were carried out on thin-wall tube samples obtained from an area planted several years ago. The results are illustrated on Figure 9. The cohesion is calculated from the difference in soil strengths of samples with and without roots. These indicate that the grass will meet the design requirements for depths up to 350 mm. For the few areas where a steeper slope requires deeper reinforcement (up to 0.45 m), the grass was supplemented with rooted hybrid poplar cuttings known to establish roots quickly under local conditions.

One thing about a biotechnical facing is that it does not provide rapid strength like shotcrete. Therefore it is important to rely on shallow soil suction for several weeks or months until the roots are in place. An unsaturated analysis with the effects of soil (matric) suction was carried out (Fabius et al 2004), indicating that at least 50 kPa of suction had to be maintained in the short term. The soil water characteristic curve (SWCC) was estimated for each soil type based on a published grain-size database (using SOILVISION software by Soilvision Systems) and indicated that no more than 40% saturation could be accommodated to maintain this suction. This was considered a low risk for the normal level of moisture in the soils at this site. Furthermore, in the event of saturation from severe and prolonged rainfall the expected sloughing would be localized and less than 0.5 m deep and easily repairable. In fact, no surface erosion or loss of vegetation occurred before the vegetation established itself.

An alternate facing method was developed for 2 localized

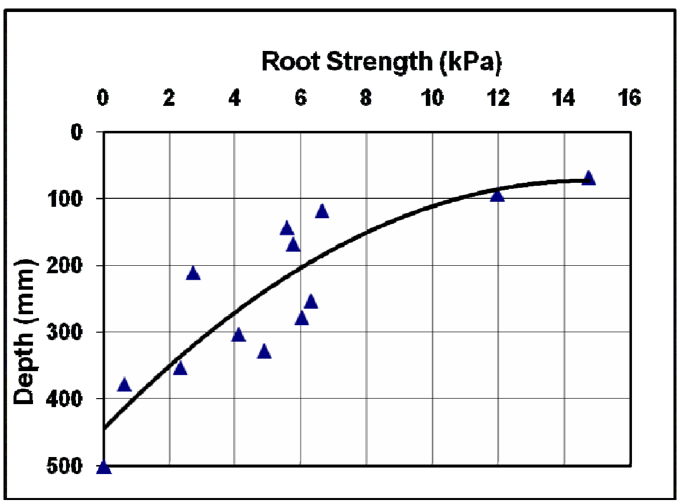

Fig. 9. Root strength from direct shear tests.

areas of the 5 sites to address zones where past slides had left a near vertical scarp. It was found that the angle of internal friction for fill material placed here needed to be at least 8 degrees higher than the angle of the slope surface (for slopes no steeper than 34^o) in order to achieve a strength equivalent to the design root cohesion. A well-graded and durable rockfill with the required strength was selected and placed after driving the nails with final level of their heads just below the rockfill design grade.

Construction

The construction of the SNART system has been described by Fabius et al (2006). The soil nails were installed using small equipment working on the slope (Figure 10). This spider-like walking excavator has 4 legs (2 of which have wheels) and an excavator arm. It can easily work on slopes up to 45^o. A

Fig. 10. Soil nails with plate heads

percussion hammer adapted for driving soil nails was mounted on the arm (Figure 11). Minor grade adjustments were made where steep scarps remained.

The 35 mm diameter steel bars were inserted in 4.5 m lengths using percussion methods. Lap splices with field welds were used. The nail heads were driven to embedment just below the slope surface. A few nails were flagged for long term monitoring of nail heads movements in order to confirm design predictions.

A community communications plan was developed in consultation with the local authorities, and the neighbourhood became quite involved in observing the day-to-day construction activities. The most frequent response was how little impact the project had on the community when compared to the massive soldier pile and lagging wall previously installed nearby.

Fig. 11. Rapid installation of soil nails by percussion.

The slope was thereafter planted with the design grass seed and, where required, the hybrid poplar. A biodegradable straw matting was pegged onto the slope to reduce interim soil and seed erosion during rainfall. Shrubs were planted at the crest of the slope for aesthetic purposes.

Concerns with respect to the safety of workers on an essentially unstable slope were addressed with a monitoring approach. During the work, a sliding pipe underground detector (SPUD) system was installed as a simple way to monitor the slope for any signs of impending instability. A SPUD is simply a plastic casing embedded vertically into the ground at the crest using a conventional hollow stem auger geotechnical drill rig. A short piece of pipe that slides inside the casing is designed to jam if its curvature exceeds the maximum deformation allowance selected. The pipe is left on the end of a wire at the bottom of the casing. Pulling the pipe up a few times per day warns the crew if movement greater than the alert level has occurred. If a grooved inclinometer casing is used, then an inclinometer can be used to more accurately profile ant detected underground movement. None of the SPUDs indicated movement during the construction.

Post Construction Performance

The nail installation was completed in 2004, and post construction monitoring was performed through a total station survey of selected nail heads on the slope at each site. Results are illustrated on Figure 12. These indicate a horizontal surface movement of less than 15 mm. The accuracy of the survey is estimated to be +/-10 mm, and therefore much of the movement is likely a result of the survey methods. Frost action may also contribute to some of the movements. The results are less than the 20 mm calculated, and less than the 25 mm deformation criteria established for the system design.

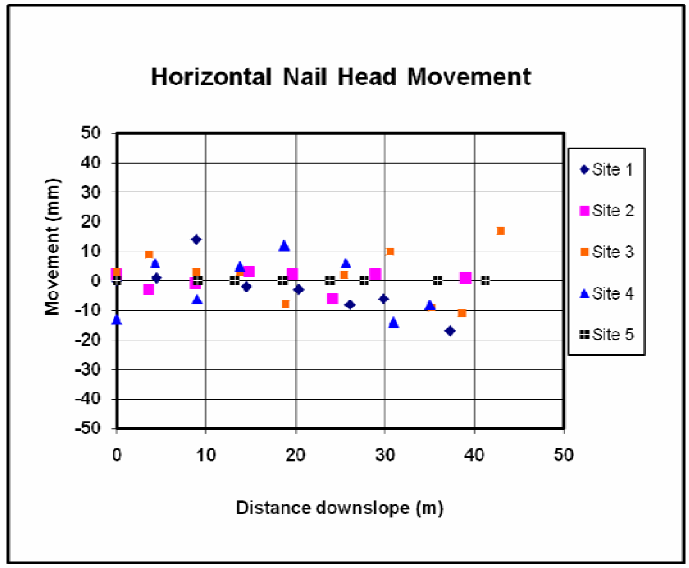

Fig. 12. Results of nail head monitoring

Over the 3 years of monitoring, no cracks or sloughing have been observed on or near the slope.

CONCLUSIONS

Five areas along the Kaministiquia River have been stabilized with an innovative and cost-effective slope stabilization system: soil nail and root technology (SNART). The system, developed in the 1990's, was proposed in response to the request for a design-build solution to a landslide hazard endangering municipal infrastructure. The system is a hybrid reinforcement and retention system, incorporating 3 proven technologies: soil nails, laterally loaded piles and biotechnical stabilization.   The owner specified an engineered design, a proven technology, no construction impacts on the street at the crest or the river at the toe, a safety factor not less than 1.3 and a 75-year design life.

SNART has developed with suitable analytical techniques, light and rapid installation equipment, efficient splicing techniques, special nail heads and a natural root reinforced facing. It has been applied to soil slopes less than 45^{o}. Design methods integrate conventional slope stability analysis with a nail resistance versus depth function, and address all failure modes including shallow soil flow around the nails.

The stabilization system for the silt slopes of the Kaministiquia River incorporated the following:

- a nail design based on bending rather than tension
- 35 mm diameter, 400 MPa, steel nails, 4 to 12 m long on a 1.0 to 1.5 m spacing
- nail heads widened with plates to stop shallow flow failures around nails
- a sacrificial allowance for long term corrosion
- a root facing to stop failures between the nails

- a design root depth of typically less than 300mm using grass, and some steeper areas with 450 mm deep roots using plantings.
- predicted deformations of not more than 20 mm.
- a final natural appearance with nails completely below the ground surface

Three years of monitoring have indicated adequate performance for all 5 sites, with surface movements not exceeding 20 mm.

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